

# THE ORIGIN OF BLUE CORES IN HUBBLE DEEP FIELDS E/S0 GALAXIES.

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*submitted to ApJL May 23, 2001*

## ABSTRACT

In this letter we address the problem of the origin of blue cores and inverse color gradients in early-type galaxies reported in the Hubble Deep Field North and South (HDFs) by Menanteau, Abraham, & Ellis (2001). We use a multi-zone single collapse model. This model accounts for the observed blue cores by adopting a broad spread in formation redshifts for ellipticals, allowing some of these galaxies begin forming no more than  $\sim 1$  Gyr before the redshift of observation. The single-zone collapse model then produces cores that are bluer than the outer regions because of the increase of the local potential well toward the center which makes star-formation more extended in the central region of the galaxy. We compare the predicted  $V_{606} - I_{814}(r)$  color gradients with the observed ones using the redshift of formation ( $z_F$ ) of the elliptical as the only free parameter. We find that the model can account with relatively good agreement for the blue cores and inverse color gradients found in many spheroidals and at the same time for the red and smooth colors profiles reported. Based on the model our analysis suggests two populations of field ellipticals, one formed recently, within  $\lesssim 1$  Gyr and another much older formed  $\gtrsim 4$  Gyr since the redshift of observation.

*Subject headings:* galaxies: elliptical, lenticulars—galaxies: formation—galaxies: evolution

## 1. INTRODUCTION

The study of field elliptical galaxies has seen a dramatic boost in the past couple of years, mainly from the realization that these systems can be objectively used to test opposed models of galaxy formation.

For a number of years it was accepted the hypothesis that field elliptical galaxies formed in isolation during a single burst of formation at high redshift. This had its origin in the early monolithic collapse model postulated by Eggen et al. (1962) and later sustained by observations of ellipticals in rich clusters over a wide redshift range which closely follow a number of “fundamental relations”. The low scatter in the fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987) and in the color-magnitude relation (CMR) (Sandage & Visvanathan 1978; Bower et al. 1992; Ellis et al. 1997; van Dokkum et al. 1998) implied a high degree of homogeneity in the stellar population, both consistent with a model in which ellipticals formed at high redshift and since then passively evolved.

On the other hand, in hierarchical CDM models (White & Rees 1978; White & Frenk 1991) galaxies are formed only as the result of merging of smaller sub-units, suggesting that massive ellipticals could only have been assembled recently (since  $z \simeq 1$ ) and in consequence there would be a paucity of early-types at higher redshifts (Kauffmann et al. 1996). Unfortunately, much of the observations were early focused on elliptical galaxies in rich clusters, where the existence of old ellipticals at high redshift is expected in hierarchical CDM models because evolution is accelerated in these dense regions (Governato et al. 1998; Kauffmann

et al. 1999).

Several studies have attempted to test whether field ellipticals were formed at high redshift and evolved in isolation since, following to some extent the methodology from Moustakas et al. (1997) and Zepf (1997), consisting of using a combination of optical and infrared colors for selecting spheroidals in search for a decline in the co-moving density of spheroidals; all of them with consistent results, a significant lack of red objects compared with the predictions of pure luminosity evolution (PLE) models (Barger et al. 1999; Daddi et al. 2000). The addition of HST imaging lead to the conclusion that a model with constant co-moving density and a single epoch of formation for E/S0 at *all* epochs is ruled out. A more conclusive test in this line will need a complete census of ellipticals up to  $z = 1$ , recent results from Im et al. (2000) are inconclusive but compatible with very mild density evolution. Similarly, using dataset multicolor information it has been reported a population of E/S0 with colors significantly bluer than passive evolution (Kodama et al. 1999; Abraham et al. 1999). In a recent detailed analysis Menanteau, Abraham, & Ellis (2001) reported, using resolved multicolor photometry of E/S0 in both HDF-North and South, solid evidence for the continuous star-formation in E/S0 galaxies. The resolved ( $V - I$ ) data revealed a population of spheroidals with central blue cores, color inhomogeneities and inverse color gradients, which were indicative of formation activity at the galaxies redshift of observation. Interestingly, a subset of spheroidals had the color properties of old stellar population in good agreement with the ones prescribed with a stellar population formed in a single burst at  $z > 2$ .

In recent years, the hierarchical CDM semi-analytical

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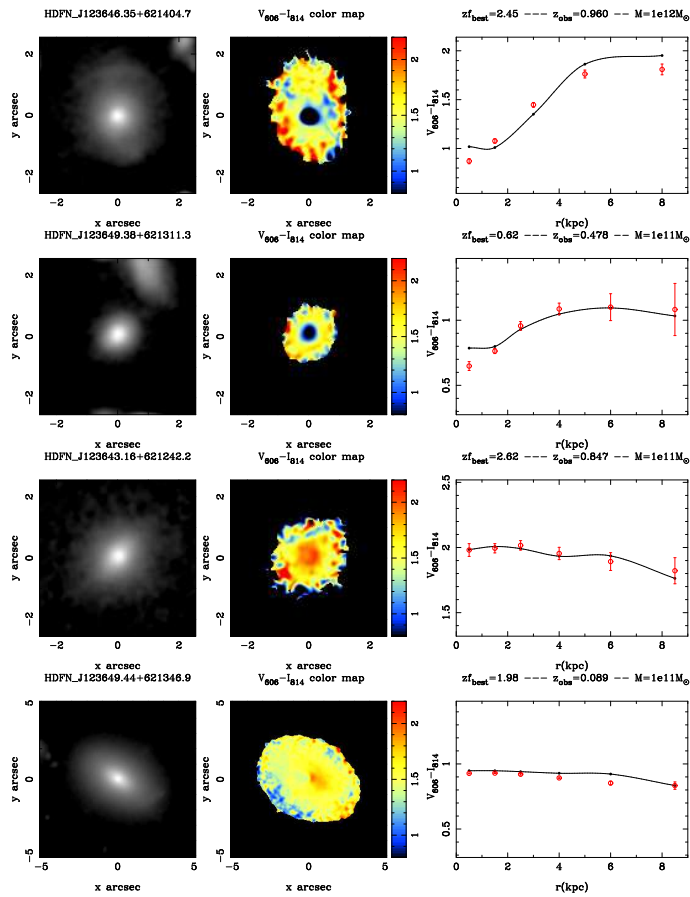


FIG. 1.— An example of the ability of the model to reproduce a range of different color gradients. Figure shows from left to right:  $I_{814}$ -band surface brightness map,  $V_{606} - I_{814}$  color pixel map and  $V_{606} - I_{814}(r)$  color gradient for several E/S0 in the sample. Open circles represent observed gradients while solid lines the model predictions. The complete set of fits can be found at <http://www.ociw.edu/~felipe/blue-cores>

models have dominated the predictions in the field leaving alternative frameworks relatively unexplored in which to interpret data. The realization that spheroidals, even at intermediate redshifts, are a mixture of both a mild star-forming and old stellar population, makes imperative to search for alternative formation models which can successfully reproduce both properties, the blue cores and smooth color profiles observed. In the past, some authors have investigated the effect of adding small amounts of SF activity to account for some of the blue colors observed in E/S0 (e.g. Menanteau et al. 1999, Trager et al. 2000). Although they have been successful to some extent in reproducing the observed colors, they rely on somewhat ad-hoc recipes.

Recently, Friaca & Terlevich (2001) have used a multi-zone chemo-dynamical model to predict the color gradients of spheroidals at different redshifts. In their model an important component to reproduce the blue cores is a late infall of gas that extends the duration of the star formation. In this letter we investigate a similar model but without the late infall feature and take it a step further by producing detailed fits to the observed color gradients of all 77 E/S0 studied by Menanteau, Abraham, & Ellis (2001) in order to assess whether such single-collapse models really fit the observations at all radii and not only the qualitative

trend of a blue core. We show that the color gradients are determined by the shape of the gravitational potential and therefore the different escape velocities of the gas rather than the need of late infall. In our model the majority of the gas ( $> 80\%$ ) is assembled at a very early epoch in the formation of the elliptical. This model could be representative of how ellipticals assemble in a warm dark matter scenario (where small scale structure is suppressed) or in a CDM scenario in which the subsequent merging of small objects on a big galaxy has been suppressed –maybe due to the lack of small scale power (e.g. self-interacting dark matter) or strong feedback from the big central galaxy.

## 2. THE HDF NORTH AND SOUTH E/S0 SAMPLE

The E/S0 used in our analysis are taken from the field sample of galaxies selected by Menanteau, Abraham, & Ellis (2001) from the HDFs. Here we include a brief description of it, but we point the reader to Menanteau, Abraham, & Ellis (2001) for a complete description of it. The sample consists of 77 spheroidal galaxies, classified as E, E/S0 and S0 under the Hubble scheme with a limit near-total magnitude of  $I_{814} = 24$  mag. Throughout this letter magnitudes are in the Vega system. Source detection and integrated photometry were taken from Sextractor catalogs constructed by the Space Telescope Science Institute following the IAU IDs given there. The morphological selection of E/S0 was performed using both visual and machine based classification in order to ensure a robust morphology selection (see Menanteau, Abraham, & Ellis 2001). Redshift information was taken from publicly available compilations, and augmented with photometric estimates provided by S. Gwyn (private communication).

### 2.1. Observed color gradients

The quantity that we use to compare the properties of spheroidals with the model predictions (see next section) is the color gradient of galaxies. We focus only on the  $V_{606} - I_{814}$  colors to estimate the color gradient  $V_{606} - I_{814}(r)$  as a function of the radius  $r$ , given that these represent the bands with higher signal-to-noise in both HDFs. In order to obtain the color gradients, we first compute the centroid and second order moments ( $\overline{x^2}$ ,  $\overline{y^2}$ ,  $\overline{xy}$ ) of the galaxy utilizing the  $I_{814}$ -band, from which we estimate the ellipticity parameters of the objects ( $A, B, \theta$ ). It is worth noting that we keep the same elongation ratio  $e = A/B$  up to the isophotal limit to which the color gradient is computed. Finally using concentric ellipses, we compute the  $V_{606} - I_{814}(r_i)$  gradients as the median color in the shell between  $r_{i-1}$  and  $r_{i+1}$ .

## 3. MAKING AN ELLIPTICAL

We model elliptical galaxies as a system with spherical symmetry and multiple zones. In particular it is assumed that the bulk ( $> 80\%$ ) of the gas in this model was in place at the time of formation and was able to form stars, i.e. was cool enough. The galaxy is then divided in spherical shells –100 for the present case– each of them independent, i.e. no transfer of gas is allowed among shells. In each of these shells star formation proceeds according to a Schmidt law:  $\text{SFR} = \nu \rho_{\text{gas}}(t)$ , where  $\rho_{\text{gas}}(t)$  is the volume gas density in the shell and  $\nu = 8.6(M_{\text{gas}}/10^{12}M_{\odot})^{-0.115}\text{Gyr}^{-1}$ .

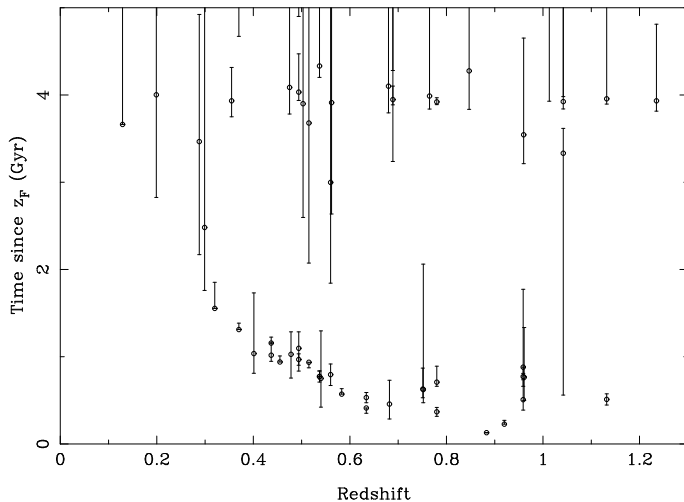


FIG. 2.— Time since the most likely redshift of formation ( $z_F$ ) for all E/S0 in the HDFs sample as a function of its redshift of observation.  $z_F$  is calculated as described in the text. Error bars represent  $1\sigma$  values on the  $\chi^2$  fitting.

The initial mass function is assumed to be a power law ( $\phi(m) \propto m^{-0.95}$ ). Star formation proceeds in each shell until the gas is heated up by SN to a temperature  $T$  that corresponds to the escape velocity of *each* shell (see Martinelli, Matteucci, & Colafrancesco 2000 for a detailed description of the model). The gas in the elliptical galaxy is assumed to be within a dark matter halo of mass 7 times larger than the gas mass ( $\Omega_m = 0.35$  and  $\Omega_b = 0.05$ ). The dark matter follows the density profile described in Martinelli, Matteucci, & Colafrancesco (2000). The chemical enrichment of the gas and stars is followed in detailed using the stellar yields of Woosley (1987) for massive stars and supernovae II ( $M > 8M_\odot$ ), Renzini & Voli (1981) for low and intermediate mass stars ( $0.8 \leq M/M_\odot \leq 8$ ) and Thielemann, Nomoto, & Hashimoto (1993) for SN type Ia; we also took into account the lifetimes of stars. For each shell we assume that mixing of the gas is very efficient in the whole shell and shorter than the lifetime of the most massive stars.

For different masses the model predicts a different time dependence of the SFR. In more massive systems the potential well will be deeper and therefore it will take longer for the gas to reach temperatures larger than the escape velocity in the potential, thus star formation will last longer than in less massive systems. Also, for a fixed mass, since the potential is deeper in the core of the galaxy, the model predicts that star formation will last longer in the core than in the outer regions (see Martinelli, Matteucci, & Colafrancesco 2000). The model provides us with the mass fraction that is turned into stars at a given time and their chemical composition. This output is then fed into a synthetic stellar population code (Jimenez et al. 1998) to compute the spectral properties of the galaxy at different radii and times.

#### 4. RESULTS

The aim of our analysis is to directly compare the observed  $V_{606} - I_{814}(r)$  color gradients with the predictions of the above model. In the first place we are interested to see whether the color gradients can be reproduced at all.

We note that the only free parameter now in our model is the redshift of formation given that mass is determined by the brightness of the galaxy at the redshift of observation. To accomplish this we use a maximum likelihood method ( $\chi^2$ ) to compute the most-likely redshift of formation ( $z_F^{best}$ ) for the best-fitting model. In order to avoid spurious results from small fluctuations in the gradients due to noise, the model and data gradients were re-binned to a common grid of 5 – 6 shells up to a maximum physical radius of 10 kpc. In order to transform the observed color gradients to physical (kpc) length, we assumed a flat cosmology with  $\Omega_m = 0.35$  and  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Finally, as the HST point spread function (PSF) is wavelength dependent, in order to properly compare observed and modeled gradients, we convolved each modeled surface brightness profile with a 1D radial Gaussian PSF of different FWHM in the  $V_{606}$  and  $I_{814}$ -band (Casertano et al. 2000).

We applied this methodology to the whole sample of 77 E/S0 galaxies. To illustrate the method, in Figure 1 we show a selection of four representative galaxies in the sample. We can see how the model can successfully account for the observed range of  $V_{606} - I_{814}(r)$  color gradients. The complete set of fits can be found at <http://www.ociw.edu/~felipe>. It is worth noting the ability of the model to reproduce the blue cores (inverse steep gradients) present in the sample (Figure 1 upper two panels), both the color difference and the physical scale at which this occurs. In addition very flat and smooth color profiles can be successfully reproduced (Figure 1 lower two panels) as expected from a stellar population formed in single burst at high redshift. To emphasize the power of our model, we focus on the bottom panel elliptical at  $z = 0.089$ . This exhibits a slightly red color profile induced by a metallicity gradient, which the model naturally accounts for due to the different rate at which star formation proceeds in each shell yielding to a metallicity gradient.

The redshift of formation is the relevant measurement in our analysis. This is of importance to understand when E/S0 assembled to their final morphological shape in which we see them today. Figure 2 shows the time since  $z_F^{best}$  (computed galaxy redshift of formation) as a function of the observed redshift for the whole sample. The most striking feature is the bimodal distribution of times: a population seems to be formed within 1 Gyr, while a second population seems to have formed at least 4 Gyr since they were observed. We note that for the later population the time since formation could in principle be bigger than 4 Gyr, since the colors at old ages do not contain enough information as to give a precise measurement of the redshift of formation. This population, which the model predicts was assembled at an early epoch, agrees with the passive evolving population detected independently under the basis of  $\delta(V - I)$  color scatter by Menanteau, Abraham, & Ellis (2001). It is worth to notice that the model yields a relatively low redshift of formation for some galaxies when they have large inverse color gradients or marked blue colors in order to account for them.

Figure 3 shows the distribution of the formation redshift for the whole sample. The top axis shows the look-back-time. About 25% of field E/S0 in our sample have formed at  $z \gtrsim 4$ , with  $\sim 30\%$  of the sample having formed

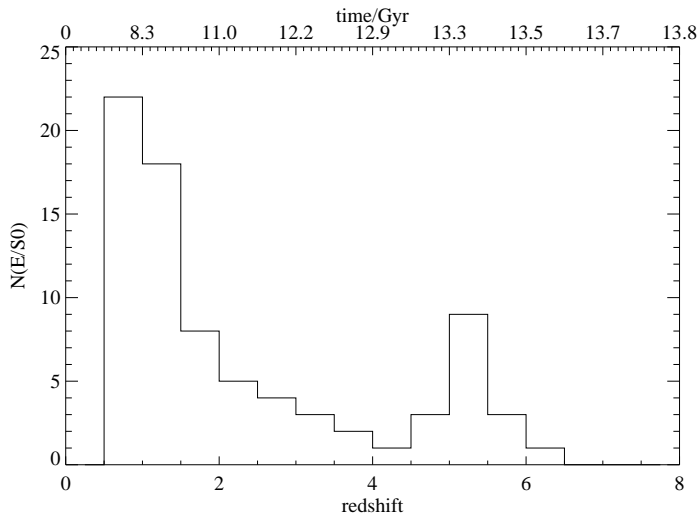


FIG. 3.— Histogram for the most likely redshift of formation,  $z_F$  values for the whole sample of E/S0.

at  $z < 1$ . The medium redshift of formation is  $z \sim 2$  and therefore the medium age of the field ellipticals in the HDFs is  $\sim 11$  Gyr. Therefore, as a whole, field ellipticals are only 1–2 Gyr younger than cluster ellipticals, in agreement with the findings by Bernardi et al. (1998) who compared the  $Mg_2 - \sigma_0$  relation for field and cluster ellipticals. The main feature of Fig. 3 is the continuous formation of field E/S0 with redshift, we do not find evidence for a *single* epoch of spheroid formation. Although for the reasons discussed above the redshift of formation can be quite uncertain at the high-redshift end, it is clear that we can distinguish a trend of a bimodal distribution in the formation redshift. This may be indicative of two preferred epochs of formation, according to the model. However, this result should not be over interpreted, as this is a model dependent one based on the success of the model to reproduce the observations.

## 5. CONCLUSIONS

In this letter we have presented an alternative approach for the formation of E/S0 galaxies. Recognizing the features that E/S0 show at low and intermediate redshift our analysis seeks to exploit the resolved information now available for E/S0 to quite high redshift focusing on their color gradients as the basis of our analysis. In order to obtain information from the color-gradients about the formation epoch of E/S0, we have adopted a multizone single collapse model for the formation of spheroids. In the context of this model, our main conclusion is that E/S0 can be properly described by a model in which 80% of the gas was processed at an early stage, but in which spheroidals are formed continuously as a function of redshift. Although there is no preferred epoch for their formation, our analysis suggest the presence of two population, one assembled recently, within  $\sim 1$  Gyr and another with the properties of an old stellar population formed  $\gtrsim 4$  Gyr from the redshift of observation. It remains to be learned what star formation histories can be obtained in a model independent fashion from the spectra of these objects and whether this yields to similar conclusions.

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